Einstein's Biggest Blunder? High-Redshift Supernovae and the Accelerating Universe

Alexei V. Filippenko

Department of Astronomy, University of California, Berkeley, CA 94720-3411 (e-mail: alex@astro.berkeley.edu)

Received ______________________; accepted ______________________

ABSTRACT

Nearly 4 years ago, two teams of observational astronomers reported that high-redshift Type Ia supernovae are fainter than expected in a decelerating or freely coasting universe. The radical conclusion that the universe has been accelerating in the past few billion years, possibly because of a nonzero value for Einstein's cosmological constant, has gripped the worlds of astronomy and physics, causing a flurry of new research. Having participated on both teams (but much more closely with one than the other), here I provide a personal, historical account of the story.

1. INTRODUCTION

An accelerating universe! A nonzero value for Albert Einstein's cosmological constant! Cosmic "antigravity"! Not even a decade ago, who would have seriously thought it? Certainly someone seeking tenure should not have made too big a deal of this possibility!

In retrospect, of course, some hints were already there (as summarized by Ostriker & Steinhardt 1995; see also Carroll, Press, & Turner 1992). For example, the calculated expansion age of the universe under the assumption that the normalized mass density (Ω_M) is equal to 1 [so that $t = (2/3)H_0^{-1}$], even with a Hubble constant (H_0) as low as 65 km s^{-1} Mpc^{-1}, is smaller than the derived ages of the oldest stars. Similarly, numerical simulations of the growth of large-scale structure in the universe are consistent with $\Omega \equiv \Omega_{\rm total} = 1$, but not if 70% of the mass-energy is in the form of hot dark matter. With the case for $\Omega_M \approx 0.3$ becoming progressively stronger, a new culprit had to be found for the remainder, if Ω really is equal to unity.

But why should $\Omega = 1$, you might ask? Because the flatness problem (i.e., we know that Ω is at least ~ 0.1 at the present time) is so compelling, and inflation (or something similar in spirit, if not in detail) provides a beautiful mechanism for the universe to achieve $\Omega = 1$. Although versions of inflation that don't demand $\Omega = 1$ were quickly generated when the observational evidence for $\Omega_M \approx 0.3$ began to pile up, the purists stuck to their guns: I remember a conference where Alan Guth was confronted with the $\Omega_M \approx 0.3$ issue, and he responded by saying that he didn't know what is going on, but he's confident that when all the dust settles, observers will measure $\Omega = 1$. I do not, however, recall that he explicitly mentioned the possibility of a nonzero cosmological constant, Λ — a "fudge factor" that had reared its ugly head several times in the past, only to be shot down by additional studies. To many physicists, the cosmological constant (like the anthropic principle) was the last refuge of scoundrels.

The initial, and most famous, appearance of Λ came in 1917, when Einstein tried to reconcile the basic property of gravity as we know it (which pulls) with the apparently static universe. But in the general theory of relativity, what gravitates is the mass-energy

density plus *3 times the pressure*, and if space has a sufficiently negative pressure (e.g., vacuum energy, or some kind of rolling scalar field or "quintessence"; e.g., Caldwell, Davé, & Steinhardt 1998), it will experience repulsion. A positive cosmological constant, should it exist, would have the requisite negative pressure; it is a vacuum energy whose density is constant, being a property of space itself. Einstein set it equal to the precise value needed for a stationary universe, even though the idea was repulsive (pun intended): there was no other evidence for a nonzero value of Λ, such a value implied that the spacetime curvature of completely empty space is nonzero, and it led to a mathematically unstable solution (the universe had to be finely balanced between expansion and contraction).

In 1929, when Edwin Hubble announced that the current recession speeds of galaxies are proportional to their distances, the entire physical and philosophical motivation for a nonzero Λ vanished; the universe is expanding, not static. Einstein renounced his cosmological constant, calling it the "biggest blunder" of his career; had he not insisted on its presence, he could have predicted the dynamic nature of the universe before other physicists such as Friedmann and Lemaître had done so (though he might have expected the universe to be contracting). But the cosmological constant itself is not a mathematical blunder; rather, it is like a constant of integration whose value must be determined. Einstein's "blunder" was in giving Λ the precise value needed for a static universe — but he couldn't have known what would transpire in the last decade of the millennium.

The events that unfolded were dramatic indeed. Now, at the turn of the millennium, the case for $\Omega_\Lambda \equiv \Lambda c^2/(3H_0^2) \approx 0.7$ is quite strong, though not yet certain. First, the data on high-redshift Type Ia supernovae (SNe Ia) were published (Riess et al. 1998b; Perlmutter et al. 1999): high-redshift ($z \approx 0.5$) SNe Ia are about 25% fainter than expected in a universe that has $\Omega_M = 0.3$, and $\sim$15% fainter than expected in a freely coasting universe ($\Omega_M = 0$), suggesting that the expansion of the universe is accelerating with time. The data imply that $\Omega_M - \Omega_\Lambda \approx -0.4$, so if $\Omega_M > 0.0$, then $\Omega_\Lambda > 0.4$. Second, measurements of the predominant angular size of fluctuations in the cosmic microwave background radiation (CMBR; de Bernardis et al. 2000; Balbi et al. 2000; Hanany et al. 2000; Jaffe et al. 2001) show that the spatial geometry of the universe is flat, and this requires $\Omega = 1$. If $\Omega_M \approx 0.3$

(see, e.g., Bahcall 2000 for a summary), then $\Omega_\Lambda \approx 0.7$. Third, the results of various deep galaxy redshift surveys, most notably the Two-Degree Field Galaxy Redshift Survey (Peacock et al. 2001; Efstathiou et al. 2001), are inconsistent with a universe dominated by gravitating dark matter. The implication is that about 70% of the mass-energy density of the universe consists of some sort of vacuum energy or "dark energy" (*not* to be confused with dark matter!) whose gravitational effect is repulsive — a kind of "cosmic antigravity." Wouldn't Einstein have been surprised to learn that his banished cosmological constant had been resurrected — not for the reason he had invoked (a static universe), but with a different value, to account for an *accelerating* universe!

Here I present my personal view of the role that research on Type Ia supernovae had on this exciting development. As the only person who at various times was a member of both of the competing teams (the Supernova Cosmology Project [SCP] and the High-z Supernova Search Team [HZT]), I perhaps have a unique perspective on the story. Of course, my view may not be free of biases, especially given my much closer and more recent association with the HZT than with the SCP. This is, by necessity, a brief summary; a much lengthier popular account, as viewed by an outsider, has been published by Goldsmith (2000; see also Livio 2000; Krauss 2000). There are numerous technical reviews, such as those by Filippenko & Riess (1998, 2000), Goldhaber & Perlmutter (1998), Goobar et al. (2000), Riess (2000), and Leibundgut (2001).

2. EARLY HISTORY

Classical, hydrogen-deficient SNe Ia are believed to result from the explosions of white dwarfs in binary systems. In contrast, hydrogen-rich SNe II signal the deaths of massive stars through core collapse and neutrino-induced rebound, perhaps in some cases aided by jets. (For a summary of observations, see Filippenko 1997; recent theoretical reviews have been written by Hillebrandt & Niemeyer 2000 and Burrows & Young 2000.] Both kinds of explosions are very luminous, making them potentially visible at high redshifts.

The utility of SNe Ia and SNe II for determinations of the Hubble constant is discussed

by Branch (1998) and by Schmidt et al. (1994), respectively. But a measurement of the deceleration parameter (q_0) requires SNe at much greater distances. Wagoner (1977) suggested that the distances of SNe Ia and SNe II at redshift $z \approx 0.3$ could be measured with the expanding photosphere method (Kirshner & Kwan 1974), while Colgate (1979) believed that the more luminous SNe Ia, being nearly "standard candles," could be used at $z \approx 1$ to determine the values of q_0 and Λ. Tammann (1979) presented some of the fine points (e.g., K-corrections, host galaxy extinction, time dilation) that would need to be considered for reliable results. Goobar & Perlmutter (1995) explicitly showed how Ω_M and Ω_Λ can be determined independently, given enough SNe Ia spanning a wide range of redshifts.

The first long-term, serious attempt to use SNe Ia for the determination of q_0 was made by a Danish-led team using a 1.5-m telescope at the European Southern Observatory (Hansen et al. 1989; Nørgaard-Nielsen et al. 1989). They obtained CCD images of clusters of galaxies repeatedly over the course of many months, and searched for new objects (potential supernovae) in them by using modern image-processing techniques. From their single definitive SN Ia (SN 1988U, $z = 0.31$) they were able to constrain q_0 to be between -0.6 and 2.5, but the project was terminated after only about 2 years, largely because of the low discovery rate. In a sense, the Danish group's project was attempted too early (before adequate computing power was available), with a small telescope and narrow field of view, and with early-generation CCDs. But they were important pioneers, showing in principle that their method of multi-epoch imaging and careful data processing can lead to the discovery of high-redshift SNe.

In the early 1990s, Hamuy et al. (1993) used a similar technique of repetitive imaging (in this case photographic) at the appropriate lunar phases to conduct the very successful Calán-Tololo search for relatively nearby SNe. In addition, the Berkeley Automated Supernova Search Team, initiated by Richard Muller and Carl Pennypacker of the Lawrence Berkeley National Laboratory (LBNL), used a CCD camera on a small telescope at the University of California, Berkeley's Leuschner Observatory to find many nearby supernovae (Pennypacker et al. 1989; Perlmutter et al. 1992), among them the well-observed SN 1990E

(Schmidt et al. 1993). Studies of nearby SNe are very important; cosmological parameters are deduced from *comparisons* of the peak apparent brightnesses of SN at high redshifts and low redshifts.

3. THE NEXT STEPS

Led by Saul Perlmutter of LBNL, the SCP formed in 1988, pushing forward the original goal of Richard Muller and Carl Pennypacker to use high-redshift SNe Ia to measure q_0 (Pennypacker et al. 1989). This was a large international team that included some astronomers, but its clear center of activity was LBNL, and it consisted largely of people trained within the physics community. I was not on the team when it first formed, but I joined in 1993 because of my astronomical expertise (especially in the field of SNe) and my spectroscopic experience with large telescopes. Specifically, I was to conduct the spectroscopic confirmation and analysis of the SN Ia candidates with the Keck telescopes, and to offer advice on getting the best possible results from the SNe.

Although I was enthusiastic about participating in the collaboration, I did not view it as the "opportunity of a lifetime"; back then, SNe Ia appeared to be marginal standard candles, with a dispersion in peak luminosity (~ 0.5 mag) about twice as large as the difference in apparent magnitude expected at $z \approx 0.5$ in $q_0 = 0$ and $q_0 = 0.5$ universes. Moreover, I thought that at best, we would find $q_0 \approx 0.5$ ($\Omega_M \approx 1$), as expected from the then-favorite theoretical model (the Einstein-deSitter universe), but that the precision of our measurement would be insufficient to determine whether the universe is open (and hence eternally expanding) or closed (eventually collapsing). This would especially be the case if standard inflation dictated the early history of the universe: Ω_M would differ from unity by an infinitesimal, unmeasurable amount. In addition, there were differences in culture and perspective that I found difficult to overcome, but I stayed with the team and contributed as best I could.

To search for high-z SNe, the SCP employed large-format CCDs on wide-angle cameras attached to large-aperture telescopes; the first such imaging system (with an $f/1$ focal

reducer) was designed for the 3.9-m Anglo-Australian Telescope. They also used newer, improved image-processing and analysis techniques, having modified the software developed for their search for nearby SNe (Pennypacker et al. 1989). The SCP was the first group to show that SNe could be found in "batches" (e.g., Perlmutter et al. 1994), at times prescribed in advance so that sufficient follow-up observations could be scheduled. This was a highly significant achievement. Initially it was difficult for the team to secure sufficient telescope time for their search, since they had not yet discovered any distant SNe — yet to demonstrate success, they needed access to large telescopes. Moreover, there was growing concern in some sectors of the supernova community that their project would not yield reliable results even if high-z SNe could be found; the measured dispersion of nearby SNe Ia when treated as perfect standard candles was ~ 0.5 mag (e.g., van den Bergh 1992; Branch & Miller 1993), some extreme deviants had been identified (Filippenko et al. 1992a,b; Phillips et al. 1992; Leibundgut et al. 1993), and it was unclear whether the extinction would be adequately taken into account.

But the SCP pressed on, optimistic that with a growing understanding of SNe Ia, a method would be found to correct for the apparent heterogeneity of SNe Ia (other than to eliminate obvious outliers in the derived Hubble diagram). They had crucial financial assistance and moral support from LBNL (funded by the Department of Energy) and from the Center for Particle Astrophysics at the University of California, Berkeley (an NSF Science and Technology Center led by Bernard Sadoulet). Their first discovery was SN 1992bi (Perlmutter et al. 1995a; $z = 0.458$ for the host galaxy; no spectrum of the supernova itself was successfully obtained). This yielded a tentative measurement of $q_0 = 0.1 \pm 0.3 \pm 0.55$ (assuming $\Lambda = 0$).

An important paper by Mark Phillips (1993), who was a staff astronomer at the Cerro-Tololo Interamerican Observatory (CTIO), led to a major improvement in the cosmological utility of SNe Ia. Using about 10 nearby, well-calibrated SNe Ia in galaxies of known distance, he showed that luminous SNe Ia exhibit a slower decline from maximum brightness than those having low peak luminosity. Although a few previous astronomers had suggested such a relation, it had always been viewed with suspicion because the data

were poor. Phillips used excellent light curves (derived in part by Nick Suntzeff, who was also at CTIO) and showed beyond reasonable doubt that the relation exists. This paved the way for precise distance measurements using SNe Ia: the objects were not exactly "standard candles," but deviations from the nominal luminosity could be taken into account by measuring the light-curve decline rate. The method was further quantified by Riess, Press, & Kirshner (1995), by Hamuy et al. (1996a,b), and by Perlmutter et al. (1997). Moreover, by utilizing light curves obtained through multiple filters, Riess, Press, & Kirshner (1996) showed that the SN extinction could be measured and removed in each individual case.

By 1994, the total number of high-z SNe found by the SCP was 7, all presumed to be SNe Ia (although a few were not spectroscopically confirmed as such). The project began to gain considerable attention, both in the astronomical community and the public eye (see, e.g., the PBS "Mysteries of Deep Space" program, episode 2, "Exploding Stars and Black Holes"). An analysis of these first 7 objects suggested $\Omega_M = 0.88 \pm 0.6$ (for $\Omega_\Lambda = 0$; or $\Omega_M = 0.94 \pm 0.3$ for $\Omega = 1$), a result that was published by Perlmutter et al. (1997). Many astronomers, however, were skeptical, especially those unfamiliar with the Phillips (1993) relation and its subsequent refinements; they expressed significant reservations about the cosmological utility of SNe Ia. Also, a high-density universe seemed at odds with other, independent measurements of Ω_M. Indeed, although I was a member of the SCP, I was wary of our conclusion; no corrections for extinction had been made, for example, and the small sample size made it prone to errors produced by deviant SNe Ia.

Motivated in part by the Phillips (1993) relation for calibrating SNe Ia, by the scientific importance of a measurement of q_0, and by the success of the SCP in finding high-z SNe Ia, a competing team (the HZT) was formed in 1994 by Brian P. Schmidt and Nick Suntzeff. Schmidt had recently completed his doctoral work under Bob Kirshner at the Harvard/Smithsonian Center for Astrophysics (CfA), and has been at the Mt. Stromlo and Siding Spring Observatories (Australia) since the beginning of 1995. Like the SCP, the HZT was an international team — but in contrast to the SCP, it consisted primarily of astronomers, many of whom had made careers studying supernovae. The HZT was structured in a less hierarchical manner than the SCP, which followed the model often

used by large-scale physics teams. The HZT had many "generals" (and, unfortunately, few "soldiers") loosely organized by the young Schmidt, who was officially elected team leader in 1996. Given what has transpired in the past few years, it is clear that having two groups was very beneficial to science — progress was accelerated (pun intended) by the competition, and results were more thoroughly checked for possible systematic errors. If a potential bias was considered by one team and not the other, for example, the second team would look bad.

The HZT searched for high-z SNe Ia with the CTIO 4-m Blanco telescope — the equipment eventually adopted by the SCP after their hard-fought initial success at the Anglo-Australian Telescope and the Isaac Newton Telescope. The observing strategy was similar to that of the SCP, with some differences in detail: obtain the first-epoch images just before first-quarter moon, the second-epoch images just after third-quarter moon, and then commence follow-up observations of identified SN candidates. Like the SCP (e.g., Perlmutter et al. 1995b), the HZT demonstrated great success in finding batches of SNe, sometimes over a dozen at a time (e.g., Suntzeff et al. 1996). When possible, the HZT's follow-up images were obtained through custom-made filters that closely matched the B and V bands redshifted by 0.35 and 0.45, thereby minimizing the K-corrections (Kim, Goobar, & Perlmutter 1996). Data reduction and analysis were also done in a broadly similar fashion, with the HZT being the first to stress proper accounting of reddening and extinction through the use of the multi-color light-curve shape technique (MLCS; Riess et al. 1996). The HZT found their first high-z SN Ia in 1995 (SN 1995K, $z = 0.48$; Schmidt et al. 1998). Its spectrum is suggestive of a SN Ia, though not completely definitive. The light curves (Leibundgut et al. 1996), however, closely resemble those of SNe Ia, suitably dilated by a factor of $1 + z$; in fact, Wilson (1939) had proposed such a test for the expanding universe. During a talk given in 1995, Goldhaber et al. (1997) also demonstrate time dilation in the SCP light curves of SNe Ia.

In the Spring of 1996, I switched from the SCP to the HZT. Although I continued to work with the SCP on some aspects of their project, such as the reduction and analysis of Keck spectra of high-z supernova candidates, my primary allegiance was with the HZT.

The switch occurred largely because of differences in style and culture: I preferred to work within the somewhat amorphous structure of the HZT, where my voice was more likely to be heard. Also, the HZT's ways of resolving issues of scientific procedures and credit were more to my liking. As was previously the case with the SCP, on the HZT I was still largely responsible for the Keck spectroscopy of SN candidates. However, I was also more closely involved with the cosmological interpretation — and indeed, a great opportunity presented itself when Adam G. Riess, formerly Bob Kirshner's graduate student at the CfA, came to the University of California, Berkeley in 1996 September as a Miller Postdoctoral Fellow to work with me.

One of Adam's first projects was to develop a quantitative method for determining the age of a SN Ia from its spectrum. His "spectral feature age" technique turned out to work remarkably well, and we were able to demonstrate that the spectrum of SN 1996bj ($z = 0.57$) evolved more slowly by a factor of $1 + z = 1.57$ than that of a nearby, low-redshift SN Ia (Riess et al. 1997). This effectively eliminated "tired light" and other non-expansion hypotheses for the redshifts of objects at cosmological distances. (For non-standard cosmological interpretations of all the SN Ia data, see Narlikar & Arp (1997) and Hoyle, Burbidge, & Narlikar 2000; a proper assessment of these possible alternatives is beyond the scope of this essay.) Although one might have been able to argue that something other than universal expansion could be the cause of the apparent stretching of SN Ia light curves at high redshifts, it was much more difficult to attribute apparently slower evolution of spectral details to an unknown effect. In a collaboration involving me, Kirshner, and SCP members Perlmutter and Peter Nugent, Adam used spectral feature ages to develop a method for determining "snapshot distances" of SNe Ia from just a single spectrum and a single night of multi-filter photometry (Riess et al. 1998a). Such distances are slightly less precise than those obtained from well-sampled SN light curves, but they have the advantage of requiring much less telescope time.

4. THE BREAKTHROUGH

In 1997, Adam was offered the opportunity to analyze and interpret all of the HZT's data to date, including 16 high-z SNe Ia and the first object (SN 1995K; Schmidt et al. 1998). He had to work quickly and carefully, yet still do a very thorough investigation. Competition from the SCP was stiff: they had already published their $\Omega_M = 0.94 \pm 0.3$ (in a flat universe) result based on 7 SNe Ia (Perlmutter et al. 1997). Moreover, they set a redshift record with SN 1997ap ($z = 0.83$), revising their estimate of Ω_M down to 0.6 ± 0.2 (in a flat universe) and to 0.2 ± 0.4 if $\Omega_\Lambda = 0$ (Perlmutter et al. 1998), and they were busy analyzing their full set of 42 SNe Ia. Meanwhile, HZT member Peter Garnavich, working as a postdoctoral fellow with Kirshner at the CfA, was in charge of the analysis of three SNe Ia for which *Hubble Space Telescope (HST)* photometry was available. Among these was SN 1997ck at $z = 0.97$, at that time a redshift record, although we cannot be absolutely certain that the object was a SN Ia because the spectrum is too poor. From the three *HST* SNe Ia and SN 1995K, Garnavich et al. (1998a) found that $\Omega_M = 0.35 \pm 0.3$ (assuming $\Omega = 1$), or $\Omega_M = -0.1 \pm 0.5$ (assuming $\Omega_\Lambda = 0$), inconsistent with the high Ω_M initially found by Perlmutter et al. (1997) but consistent with the revised estimate in Perlmutter et al. (1998). However, none of these early data sets carried the statistical discriminating power to detect cosmic acceleration.

Through the last few months of 1997, Adam's work on the HZT's full sample of 16 SNe Ia progressed rapidly to completion. During this time Adam and I often discussed the HZT science, notably on the subjects of statistical errors, potential systematic effects, and subtleties in the data calibration and analysis. In November 1997 the results seemed puzzling, indicating that if $\Omega_\Lambda = 0$, Ω_M must be negative! Adam initially checked his work for simple errors (e.g., sign errors and programming bugs), not wanting to reveal a silly error to the team. By December 1997 it was clear that something very strange had emerged from our data: the probable value of Ω_Λ was nonzero! My jaw just dropped when Adam showed me his Hubble diagram and conclusions: the high-z SNe Ia were about 0.25 mag fainter than expected in a low-density universe. This was not the answer we had expected, and many members of the HZT were worried that a subtle error had been made; indeed, Bob

Kirshner reflected that “deep in our hearts, we know this can’t be right.” On the other side of the world, in Australia, HZT leader Brian Schmidt worked hard to independently verify the analysis, making sure no obvious errors had crept in. A number of checks, however, did not reveal anything amiss — if we were wrong, it had to be for quite a subtle reason. Moreover, we began to hear that the SCP was also getting some odd, disturbing results!

A press conference was scheduled at the 1998 January AAS meeting in Washington, DC, with the stated purpose of presenting and discussing the then-current evidence for a low-Ω_M universe as published by Perlmutter et al. (1998; SCP) and Garnavich et al. (1998a; HZT). At the time, Adam did not yet feel ready to announce the possible discovery of cosmic acceleration, since various checks were still being made, and team member Peter Garnavich (who represented the HZT at the press conference) was instructed not to mention it. When showing the SCP’s Hubble diagram for SNe Ia, however, Saul Perlmutter also pointed out tentative evidence for acceleration. He stated that the conclusion was uncertain, and that the data were consistent with no acceleration; consequently, members of the press generally did not emphasize this result in their news reports. (James Glanz, in his article in the 1998 January 30 issue of *Science* magazine, was an exception.) But, of course, members of the HZT did not fail to notice that the SCP’s result pointed to the same conclusion that Adam had made from the HZT data.

In the next month, Adam worked hard to perform as many checks as possible of the astonishing result. The conclusion that the universe is currently accelerating, possibly because of a nonzero cosmological constant, did not go away. By February, Adam had completed a draft of the scientific paper describing the results (Riess et al. 1998b). Unable to find any significant problem with the measurement, we decided that I would present the result at the “Dark Matter ’98” meeting, to be held 1998 February 18–20 in Marina Del Rey, California. Gerson Goldhaber and Saul Perlmutter spoke first, discussing the SCP’s demonstration of time dilation in the SN light curves, their strong evidence for low Ω_M, and their tentative evidence for nonzero Ω_Λ. Then I gave a talk in which the HZT’s results were shown, and I stated that our data and extensive analysis strongly suggested that Λ is positive (Filippenko & Riess 1998). There was a clear feeling of excitement among the

audience — but also some disbelief and good, scientific skepticism. Rocky Kolb of the University of Chicago, for example, mentioned that the cosmological constant had come and gone at various other times in the past century, and that the case here might be no different. He said there was no obvious explanation for a value of Ω_Λ so small compared with that expected from first principles ($10^{50} - 10^{120}$), and that a value of precisely zero seemed much more likely. Later, when I gave a similar talk elsewhere, a famous physics theorist told me that our observational results *must* be wrong, since there was no conceivable way the cosmological constant could differ infinitesimally from zero.

Before the "Dark Matter '98" meeting, the HZT had not been planning to issue a press release, and a paper had not yet been submitted to a refereed journal. But rumors that we had found something very exciting had already been leaked (not by members of the HZT) to at least one reporter. I did not stick around to talk to the press after my presentation at the "Dark Matter '98" meeting; instead, I flew to the Caribbean, as previously planned, to witness the darkness of the totally eclipsed Sun. Upon my return, I found that in its 1998 February 27 issue, *Science* magazine had run a story by James Glanz entitled "Astronomers See a Cosmic Antigravity Force at Work." Brian Schmidt was quoted as saying "My own reaction is somewhere between amazement and horror, amazement because I just did not expect this result, and horror in knowing that [it] will likely be disbelieved by a majority of astronomers who, like myself, are extremely skeptical of the unexpected."

Subsequently, other newspapers picked up on the story, and within a week it had spread widely (e.g., *New York Times*, "Wary Astronomers Ponder An Accelerating Universe"). Adam Riess was busy fielding questions from the press; he was even featured on the McNeil-Lehrer News Hour and CNN's Headline News, and later in *TIME* magazine (2000 August) as one of the hottest young astrophysicists to watch in the new millennium. By May of 1998, theorists had organized a meeting in Chicago to discuss the startling results and the nature of "dark energy" — and the *New York Times* ran a story that showed two of Michael Turner's viewgraphs (one titled "Funny Energy in the Univere" [sic]). Several new television documentaries featured the HZT and SCP, including Equinox's "Big G," the BBC Horizon's "From Here to Infinity," and, most recently and thoroughly, PBS's

"Runaway Universe" (Nova). At the Chicago meeting the results were debated, and in a straw poll two-thirds of the attendees voted that they were convinced the results were correct, in part because two independent teams had reached the same conclusion.

The HZT's paper was officially accepted in May and published in the 1998 September issue of the *Astronomical Journal* (Riess et al. 1998b). With the MLCS method applied to the full set of SNe Ia, the formal results are $\Omega_M = 0.24 \pm 0.10$ if $\Omega = 1$ (i.e., $\Omega_\Lambda = 0.76 \pm 0.10$, a $> 7\sigma$ detection), or $\Omega_M = -0.35 \pm 0.18$ (which is unphysical) if $\Omega_\Lambda = 0$. The confidence contours in the Ω_M vs. Ω_Λ plane (Riess et al. 1998b) suggest that $\Omega_\Lambda > 0$ at the $\sim 3\sigma$ level; the precise results depend on the method used to analyze the light curves of SNe (MLCS, or "Δm_{15}" which is based on the total decline in the first 15 days past maximum brightness), but they are consistent with each other. The dynamical age of the universe could then be calculated from the cosmological parameters; the result is about 14.2 Gyr if $H_0 = 65$ km s^{-1} Mpc^{-1} (Riess et al. 1998b). This age is consistent with values determined from various other techniques; specifically, the recently revised ages of globular star clusters (about 13 Gyr) were no longer bigger than the expansion age of the universe. The HZT also concluded that the SN Ia data, when combined with the then-available measurements of the CMBR, show that $\Omega = 0.94 \pm 0.26$ (Garnavich et al. 1998b), consistent with a flat universe.

From an essentially independent set of 42 high-z SNe Ia (only 2 objects in common), the SCP later published their almost identical conclusions (Perlmutter et al. 1999). (Although the SCP included more SNe in their study, the error bars per object were larger than in the HZT's work, so the final answer had roughly comparable uncertainty.) This agreement suggests that neither team had made a large, simple blunder! If the result was wrong, the reason had to be subtle.

In its 1998 December 18 issue, *Science* magazine named the HZT's and SCP's co-discovery of an accelerating universe the top "Science Breakthrough of 1998." Although both teams were honored to have been recognized in this manner, they were not yet certain that they were right. However, the editors of *Science* magazine noted that rarely is an important discovery made and confirmed beyond reasonable doubt within the same year.

About 3/4 of a year had passed since the announcement of acceleration, and nobody had shot definitive holes in the analysis, so the editors of *Science* magazine felt justified in their proclamation. Their magazine cover showed a caricature of Einstein blowing a "bubble universe" out of his pipe and watching (with a very surprised expression) its expansion accelerate, while holding a sheaf of papers on which Λ can be seen. Einstein had renounced the cosmological constant in 1929, following Edwin Hubble's discovery of the expansion of the universe, but now the HZT and SCP had resurrected it — to produce not a static universe, but rather an accelerating one. Yes, he would surely have been quite surprised to learn of this development, were he alive now!

5. SEARCHING FOR SYSTEMATIC ERRORS

The conclusion reached by the HZT and SCP is so dramatic, so "crazy" in some respects, that it behooves us to find an alternative explanation — a systematic effect that causes high-z SNe Ia to appear fainter than expected. Although both teams had considered a number of potential systematic effects in their discovery papers (Riess et al. 1998b; Perlmutter et al. 1999), and had shown with reasonable confidence that obvious ones were not greatly affecting their conclusions, it was of course possible that they were wrong, and that some other culprit was leading to an incorrect interpretation of the data. The two obvious effects are cosmic evolution of the peak luminosity of SNe Ia (i.e., they were intrinsically dimmer in the past), and relatively gray extinction (since normal extinction had been taken into account by using the MLCS technique).

One way to test for cosmic evolution of SNe Ia is to compare all measurable properties of low-z and high-z SNe Ia, and see if they differ. If they don't, then a reasonable (but not absolutely iron-clad) conclusion is that their peak luminosities are also the same. For example, the HZT showed that the spectrum of a particularly well-observed SN Ia at $z = 0.45$ is very similar to that of a nearby SN Ia (Coil et al. 2000; see also Perlmutter et al. 1998; Riess et al. 1998b). Moreover, Riess et al. (2000) showed that the restframe near-infrared light curve of SN 1999Q ($z = 0.46$) probably has a second maximum about a

month after the first one, just like that of nearby SNe Ia of normal luminosity, and unlike subluminous SNe Ia such as SN 1991bg (Filippenko et al. 1992b). Additional tests with spectra and near-infrared light curves are currently being conducted.

Another way of using light curves to test for possible evolution of SNe Ia is to see whether the risetime (from explosion to maximum brightness) is the same for high-z and low-z SNe Ia; a difference might indicate that the peak luminosities are also different. Though the exact value of the risetime is a function of peak luminosity, for typical low-z SNe Ia it is 20.0 ± 0.2 days (Riess et al. 1999b). We pointed out (Riess et al. 1999a) that this differs by 5.8σ from the *preliminary* risetime of 17.5 ± 0.4 days previously reported in conferences by the SCP (Goldhaber et al. 1998; Groom 1998). However, a more thorough analysis of the SCP data (Aldering, Knop, & Nugent 2000) shows that the high-z uncertainty of ± 0.4 days that the SCP originally reported was too small because it did not account for unappreciated systematic effects and correlated errors. The revised discrepancy with the low-z risetime is about 2σ or less. Thus, the apparent difference in risetimes might be insignificant. Even if the difference is real, however, its relevance to the peak luminosity is unclear; the light curves may differ only in the first few days after the explosion, and this could be caused by small variations in conditions near the outer part of the exploding white dwarf that are inconsequential at the peak.

Let us now consider the possibility of extinction. As mentioned above, our procedure already corrects for extinction produced by normal dust grains similar to the average grains in the Galaxy. However, could an evolution in dust grain size descending from ancestral interstellar "pebbles" at higher redshifts cause us to underestimate the extinction (e.g, Aguirre 1999a,b)? Large dust grains would not imprint the reddening signature of typical interstellar extinction upon which our corrections rely. But even the dust postulated by Aguirre is not completely gray, having a minimum size of about 0.1 μm. We can test for such nearly gray dust by observing high-redshift SNe Ia over a wide wavelength range to measure the color excess it would introduce. If $A_V = 0.25$ mag, then $E(U-I)$ and $E(B-I)$ should be 0.12–0.16 mag. If, on the other hand, the 0.25 mag faintness is due to Λ, then no such reddening should be seen. This effect is measurable using proven techniques; so far,

with just one SN Ia (SN 1999Q, $z = 0.46$), the HZT's results favor the no-dust hypothesis to better than 2σ (Riess et al. 2000). More work along these lines is in progress, but not without obstacles: a 5-night HZT observing run at Keck in Fall 2000, for spectroscopic identification of high-z SN candidates, was completely washed out by bad weather! HZT team members Bruno Leibundgut and Jesper Sollerman came to the rescue with two clear nights at ESO's Very Large Telescope, the second of which had $\sim 0.3''$ seeing.

6. HINTS OF THE SMOKING GUN

The most decisive test to distinguish between Λ and cumulative systematic effects, however, is to examine the *deviation* of the observed peak magnitude of SNe Ia from the magnitude expected in the low-Ω_M, zero-Λ model. If Λ is positive, the deviation should actually begin to *decrease* at $z \approx 1$; we will be looking so far back in time that the Λ effect becomes small compared with Ω_M, and the universe is decelerating at that epoch. If, on the other hand, a systematic bias such as gray dust or evolution of the white dwarf progenitors is the culprit, we expect that the deviation of the apparent magnitude will continue growing (for example, see Figure 11 in Filippenko & Riess 2000, or Figure 13 in Riess 2000), unless the systematic bias is set up in such an unlikely way as to mimic the effects of Λ (e.g., Drell, Loredo, & Wasserman 2000). A turnover, or decrease of the deviation of apparent magnitude at high redshift, can be considered the "smoking gun" of Λ. Thus, the HZT and SCP have embarked on campaigns to find and monitor SNe Ia at $z \gtrsim 0.8$. Results for two SNe Ia at $z > 1$ measured by the HZT already look promising (J. Tonry et al., in preparation); their deviation in apparent magnitude is roughly the same as that at $z \approx 0.5$. The data would have been even more convincing had *HST* not lost its third gyro in Fall 1999, placing it in "safe mode" (and hence unusable!) during a critical time in our program.

Very recently, Riess et al. (2001) reported *HST* observations of a probable SN Ia at $z \approx 1.7$ (the most distant SN Ia ever observed) that suggest the expected turnover is indeed present, providing a tantalizing glimpse of the epoch of deceleration (Riess et al. 2001). This object, SN 1997ff, was discovered by Gilliland & Phillips (1998) in a repeat *HST*

observation of the Hubble Deep Field–North, and serendipitously monitored in the infrared with *HST*/NICMOS. The peak apparent SN brightness is consistent with that expected in the decelerating phase of the preferred cosmological model, $\Omega_M \approx 0.3, \Omega_\Lambda \approx 0.7$. It is inconsistent with gray dust or simple luminosity evolution, candidate astrophysical effects which could mimic previous evidence for an accelerating universe from SNe Ia at $z \approx 0.5$.

The possible discovery of a turnover, as well as complementary studies such as those of the CMBR, led to the cover story on the 2001 June 25 issue of *TIME* magazine: "How the Universe will End." (Adam Riess keeps good company in the story, being singled out along with Hubble, Einstein, Zwicky, Penzias, and Wilson as giants who studied the universe.) On the other hand, it is wise to remain cautious: the error bars are large, and it is always possible that we are being fooled by this one object. Clearly, more SNe Ia at such high redshifts should be found and monitored in the future to help verify the hypothesis of a currently accelerating and previously decelerating universe.

Another very important question to address is whether the "dark energy" is caused by a cosmological constant or some other phenomenon such as quintessence (e.g., Caldwell et al. 1998). If Λ dominates, then the equation of state of the dark energy should have an index $w = -1$, where the pressure (P) and density (ρ) are related according to $w = P/(\rho c^2)$. Garnavich et al. (1998b) and Perlmutter et al. (1999) already set an interesting limit, $w \lesssim -0.60$ at the 95% confidence level. However, more high-quality data at $z \approx 0.5$ are needed to narrow the allowed range.

Farther in the future, large numbers of SNe Ia found by the *Supernova/Acceleration Probe* (*SNAP*; Nugent 2000) and the Large-area Synoptic Survey Telescope (the "Dark Matter Telescope"; Tyson & Angel 2001) could reveal whether the value of w depends on redshift, and hence should give additional constraints on the nature of the dark energy. High-redshift surveys of galaxies, such as DEEP2 (Davis et al. 2001), should provide independent evidence for (or against!) Λ. And, of course, the space-based missions to map the CMBR (e.g., MAP, Planck) are designed to obtain a wealth of valuable data. We've already come a long way, but these projects and others promise to provide much future excitement as well. I never thought that I would be involved in such a fundamental

development during my career, and I am eternally grateful for the opportunity to have contributed. It's been a blast.

The following grants have generously supported my own research with the SCP and especially the HZT: NSF AST-9417213 and AST-9987438, as well as NASA/*HST* GO-7505, GO-7588, GO-8177, GO-8641, and GO-9118 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. I also acknowledge the Guggenheim Foundation for a Fellowship. The results summarized here would not have been possible without the hard work of members of the HZT and SCP, and of many other astronomers. I am especially grateful to Adam Riess for countless stimulating discussions, to Brian Schmidt for excellent leadership of the HZT, and to Saul Perlmutter for pioneering the "batch" discovery of high-redshift supernovae.

REFERENCES

Aguirre, A. 1999a, ApJ, 512, L19

Aguirre, A. 1999b, ApJ, 525, 583

Aldering, G., Knop, R., & Nugent, P. E. 2000, AJ, 119, 2110

Bahcall, N. A. 2000, Phys. Rep., 333, 233

Balbi, A., et al. 2000, ApJ, 545, L1

Branch, D. 1998, ARA&A, 36, 17

Branch, D., & Miller, D. 1993, ApJ, 405, L5

Burrows, A., & Young, T. 2000, Phys. Rep., 333, 63

Caldwell, R. R., Davé, R., & Steinhardt, P. J. 1998, Ap&SS, 261, 303

Carroll, S. M., Press, W. H., & Turner, E. L. 1992, ARA&A, 30, 499

Coil, A. L., et al. 2000, ApJ, 544, L111

Colgate, S. 1979, ApJ, 232, 404

Davis, M., Newman, J. A., Faber, S. A., & Phillips, A. C. 2001, in Proc. of the ESO/ECF/STScI Workshop on Deep Fields (Berlin: Springer), in press (preprint astro-ph/0012189)

de Bernardis, P., et al. 2000, Nature, 404, 955

Drell, P. S., Loredo, T. J., & Wasserman, I. 2000, ApJ, 530, 593

Efstathiou, G., et al. 2001, MNRAS, submitted (preprint astro-ph/0109152)

Filippenko, A. V. 1997, ARA&A, 35, 309

Filippenko, A. V., & Riess, A. G. 1998, Phys. Rep., 307, 31

Filippenko, A. V., & Riess, A. G. 2000, in Particle Physics and Cosmology: Second Tropical Workshop, ed. J. F. Nieves (New York: AIP), 227

Filippenko, A. V., et al. 1992a, ApJ, 384, L15

Filippenko, A. V., et al. 1992b, AJ, 104, 1543

Garnavich, P., et al. 1998a, ApJ, 493, L53

Garnavich, P., et al. 1998b, ApJ, 509, 74

Gilliland, R. L., & Phillips, M. M. 1998, IAU Circ. 6810

Goldhaber, G., & Perlmutter, S. 1998, Phys. Rep., 307, 325

Goldhaber, G., et al. 1997, in Thermonuclear Supernovae, ed. P. Ruiz-Lapuente, R. Canal, & J. Isern (Dordrecht: Kluwer), 777

Goldhaber, G., et al. 1998, BAAS, 30, 1325

Goldsmith, D. 2000, The Runaway Universe (Cambridge: Perseus Books)

Goobar, A., & Perlmutter, S. 1995, ApJ, 450, 14

Goobar, A., et al. 2000, Phys. Scr., T85, 47

Groom, D. E. 1998, BAAS, 30, 1419

Hamuy, M., Phillips, M. M., Schommer, R. A., Suntzeff, N. B., Maza, J., & Avilés, R. 1996a, AJ, 112, 2391

Hamuy, M., Phillips, M. M., Schommer, R. A., Suntzeff, N. B., Maza, J., & Avilés, R. 1996b, AJ, 112, 2398

Hamuy, M., et al. 1993, AJ, 106, 2392

Hanany, S., et al. 2000, ApJ, 545, L5

Hansen, L., Nørgaard-Nielsen, H. U., Jorgensen, H. E., Ellis, R. S., & Couch, W. J. 1989, A&A, 211, L9

Hillebrandt, W., & Niemeyer, J. C. 2000, ARA&A, 38, 191

Hoyle, F., Burbidge, G., & Narlikar, J. V. 2000. A Different Approach to Cosmology (Cambridge: Cambridge Univ. Press)

Jaffe, A., et al. 2001, preprint (astro-ph/0007333)

Kim, A., Goobar, A., & Perlmutter, A. 1996, PASP, 108, 190

Kirshner, R. P., & Kwan, J. 1974, ApJ, 193, 27

Krauss, L. M. 2000, Quintessence (New York: Basic Books)

Leibundgut, B. 2001, ARA&A, 39, 67

Leibundgut, B., et al. 1993, AJ, 105, 301

Leibundgut, B., et al. 1996, ApJ, 466, L21

Livio, M. 2000, The Accelerating Universe (New York: Wiley)

Narlikar, J. V., & Arp, H. C. 1997, ApJ, 482, L119

Nørgaard-Nielsen, H. U., Hansen, L., Jorgensen, H. E., Salamanca, A. A., Ellis, R. S., & Couch, W. J. 1989, Nature, 339, 523

Nugent, P. 2000, in Particle Physics and Cosmology: Second Tropical Workshop, ed. J. F. Nieves (New York: AIP), 263

Ostriker, J. P., & Steinhardt, P. J. 1995, Nature, 377, 600

Peacock, J. A., et al. 2001, Nature, 410, 169

Pennypacker, C., et al. 1989, in Particle Astrophysics: Forefront Experimental Issues, ed. E. B. Norman (Singapore: World Scientific), 188

Perlmutter, S., Muller, R. A., Newberg, H. J. M., Pennypacker, C. R., Sasseen, T. P., & Smith, C. K. 1992, in Robotic Telescopes in the 1990s, ed. A. V. Filippenko (San Francisco: ASP), 67

Perlmutter, S., et al. 1994, IAU Circ. 5956

Perlmutter, S., et al. 1995a, ApJ, 440, L41

Perlmutter, S., et al. 1995b, IAU Circ. 6270

Perlmutter, S., et al. 1997, ApJ, 483, 565

Perlmutter, S., et al. 1998, Nature, 391, 51

Perlmutter, S., et al. 1999, ApJ, 517, 565

Phillips, M. M. 1993, ApJ, 413, L105

Phillips, M. M., et al. 1992, AJ, 103, 1632

Riess, A. G. 2000, PASP, 112, 1284

Riess, A. G., Filippenko, A. V., Li, W., & Schmidt, B. P. 1999b, AJ, 118, 2668

Riess, A. G., Nugent, P., Filippenko, A. V., Kirshner, R. P., & Perlmutter, S. 1998a, ApJ, 504, 935

Riess, A. G., Press, W. H., & Kirshner, R. P. 1995, ApJ, 438, L17

Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, ApJ, 473, 88

Riess, A. G., et al. 1997, AJ, 114, 722

Riess, A. G., et al. 1998b, AJ, 116, 1009

Riess, A. G., et al. 1999a, AJ, 118, 2675

Riess, A. G., et al. 2000, ApJ, 536, 62

Riess, A. G., et al. 2001, ApJ, 560, 49

Schmidt, B. P., Kirshner, R. P., Eastman, R. G., Phillips, M. M., Suntzeff, N. B., Hamuy, M., Maza, J., & Aviles, R. 1994, ApJ, 432, 42

Schmidt, B. P., et al. 1993, AJ, 105, 2236

Schmidt, B. P., et al. 1998, ApJ, 507, 46

Suntzeff, N., et al. 1996, IAU Circ. 6490

Tammann, G. A. 1979, in ESA/ESO Workshop on Astronomical Uses of the Space Telescope, ed. F. Macchetto, F. Pacini, & M. Tarenghi (Geneva: ESO), 329

Tyson, J. A., & Angel, R. 2001, in The New Era of Wide Field Astronomy, ed. R. Clowes, A. Adamson, & G. Bromage (San Francisco: ASP), 347

van den Bergh, S. 1992, Science, 258, 421

Wagoner, R. V. 1977, ApJ, 214, L5

Wilson, O. C. 1939, ApJ, 90, 634

This manuscript was prepared with the AAS LATEX macros v4.0.